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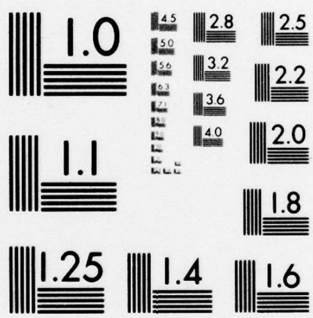
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Technical Report

THE PROCESSES OF VISUAL PERCEPTION

William R. Uttal
University of Michigan

Contract Number: N00014-77-C-0471 new
Work Unit Number: NR 197-039

Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

Air Force Office of Scientific Research
Life Sciences Directorate
Bolling AFB, D. C. 20332

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Prepared by:

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This report summarizes the contents of a book entitled The Processes of Visual Perception written during the course of this contract. The book presents a classification system of visual processes that organizes and arranges the extensive data base of perceptual science. The taxonomy consists of 6 levels:

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Level 0: Preneural Transformations;
Level 1: Receptor Transformations;
Level 2: Neural Network Transformations;
Level 3: Figural Organization Processes;
Level 4: Multidimensional Interactions; and
Level 5: Image Manipulation.

(Level 5 is not discussed in this book. It will be the topic of the next book in the series of which this present one is the third volume.)

This progress report presents a brief summary of each of the chapters in the book as well as the entire last chapter. This final epilog, entitled "Emerging Principles of Visual Perception" was the target towards which this entire research project was aimed. At the outset of the book, it was asserted that the major contribution it could make would be the statement of current thinking in the field of perceptual science. This list of principles, as well as the taxonomy itself, is a synthetic and integrative metatheory of perceptual processing as our science sees it in the last third of the twentieth century.

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ACKNOWLEDGEMENTS

This research project was an unusual one. It did not involve primary data collection but, rather, was a systematic review of a large data base, the extraction of the general implications of that data, and their synthesis into an organizing taxonomy. This project was sponsored by the Engineering Psychology Programs of the Office of Naval Research with supplemental support from the Air Force Office of Scientific Research and AMD/RDO (USAF). I am especially grateful to the ONR's Dr. Martin A. Tolcott, Director of Engineering Psychology, and Dr. John J. O'Hare, scientific officer for the project, for their encouragement throughout the course of this project. Dr. O'Hare's contributions, in particular, were far greater than his administrative responsibility would indicate. His judgment about matters of general organization and his detailed commentary on some of the chapters were especially appreciated.

The latter part of the book was written while I was on sabbatical leave at the University of Hawaii. I am grateful to Dr. Robert Cole, Chairman of the Department of Psychology there, for making that visit possible. I also was pleased to have the sabbatical extended beyond a minimum duration by a James McKeen Cattell sabbatical supplement award. The continued courtesies of Dr. Robert L. Thorndike, secretary-treasurer of the fund, throughout the course of my sabbatical are gratefully acknowledged. Much of the typing of the manuscript has been carried out by Suzanne Gurney, to whom I hereby extend my thanks for her patience with the roughness of my rough drafts.

A TAXONOMY OF VISUAL PROCESSES

I. GENERAL DISCUSSION

This project was intended to produce a systematic taxonomy and organizing synthesis of the voluminous data base of perceptual psychology with emphasis on the visual modality. The project was motivated by the belief that the literature in visual perception is so enormous that the purpose of this science--understanding of general principles--is on the verge of being submerged under the mass of the very data that are supposed to contribute to that understanding. However easy it is to agree with this truism and in spite of the fact that there is great lip service paid to the need for integration and synthesis, in fact, there has rarely been any explicit support to carry out such a program of research. The Office of Naval Research's support of integrative synthesis over the years has remained virtually unique. This agency is to be commended for the important role it plays in this regard and I am proud to acknowledge their support at this point.

It is hard to either summarize or evaluate the quality of a research project such as this present one; subsequent reviewers will have to speak to the literary and intellectual quality of this volume. It is, however, possible to give an idea of its magnitude. During the two year period of this contract, a preface and 12 chapters have been written. The content of each will be summarized in the next section of this final report but for the moment let us consider only the size of the manuscript. In brief, the double spaced page count (including footnotes) for each chapter is as follows:

Preface and other front matter	38
Chapter 1	90
Chapter 2	109

Chapter 3	126
Chapter 4	59
Chapter 5	98
Chapter 6	117
Chapter 7	100
Chapter 8	101
Chapter 9	122
Chapter 10.	86
Chapter 11.	149
Chapter 12.	32
Grand Total	1227

In addition, approximately 2000 references have been collected for a bibliography that, while not totally exhaustive, does cover what I believe are the major issues in today's perceptual science. Almost 300 figures have also been identified as being of sufficient import to be reproduced in the final volume.

Obviously this is a rather large book. However, there is nothing less meaningful than sheer volume in evaluating the various dimensions of quality that can characterize a book. That will have to be done by others when the book is published some time in 1980 following extensive revisions, insertions of new (and newly uncovered) data of relevance, review by colleagues, and finally the many stages of copy editing, typesetting, and proofreading involved in the actual publication of this volume.

One might also ask, however, how has the final version met the specifications of the originally proposed plan. Obviously the writing of a book is a dynamic process and some alterations are to be expected. In general, however, the book followed the original plan presented in 1976. As my studies progressed it became obvious that

there were certain changes that must be made. The changes that have been made are, for the most part, expansions of the original plan rather than alterations in its essential order. I did not appreciate the need at the outset for a separate consideration of the impact of the preneural processes (Level 0) that finally culminated in the insertion of Chapter 5. I did not anticipate the difficulty that the temporal interactions would pose nor that a separate chapter (Chapter 7) would be required to properly consider them. Furthermore, I had to add a chapter that dealt specifically with the conceptual and empirical arguments against indiscriminate application of a "*barefoot*" *neuroreductionism to explain perceptual* phenomena.

The major deletion from the original plan is the absence of any detailed discussion of visual cognition (Level 5). The material available in this field alone proved to be so extensive that it quickly became obvious that it was not going to be possible to include it without expanding the book beyond a reasonable size. It is currently my plan to deal with these subsequent nonautomatic, active, attentive, manipulative processes in my next book (the fourth volume in a series of which this is the third).

The main theme of this book on the preattentive aspects of visual perception and the development of a taxonomy of visual processes, is summed up in Table 1. In this table are listed the six levels that seemed to best characterize the full range of visual processing. This table emphasizes a number of important dichotomies that separate several subgroups of the levels from each other. One major division distinguishes between the preneural transformations of the external world and the optical components of the eyes, on the one hand, and those transformations occurring within the perceptual system itself, on the other. (The perceptual system is defined as the sum total of all of the mechanisms, processes, and states that occur <u>subsequent</u> to sensory transduction.)

TABLE 1

		Level	Examples
Immediate, Preattentive	Physicalistic, Deterministic, Neural	0-Preneural and Prepsychological Processing	Selective absorption of ultraviolet light by lens and macular pigment
		1-Receptor Level Processing	Analysis into trivariant code by three different cone absorption spectra
		2-Neural Network Processing	Contour enhancement (Mach Bands)
	Molar, Psychological Rationalistic	3-Figure-Ground organization and Signal Extraction Processing (Prequantitative and unidimensional)	Organization of Ishihara patterns
		4-Integration and Construction (Quantitative and multidimensional)	Color constancy and contrast; simultaneous contrast and metacontrast
Subsequent Manipulative Attentive Effortful Active.		5-Subsequent Mental Image Processing	Mental Rotation of Image

A second major division distinguishes between levels of processing that can be reduced to physical or neural terms and those that cannot. The first of these two groups includes those levels of transformations that can plausibly be attributed to relatively simple, deterministic processes in the external world, as well as in both the receptors and the identifiable neural networks of the peripheral nervous system. The second group includes those transformations that can only be described in a molar and phenomenological language.

A third major division distinguishes between the automatic, preattentive processes that I have chosen to include within the rubric of perception for the purposes of this book and the more active information processing tasks that are included within the rubric of visual cognition or thinking.

There are several other important features of this classification system also implicit in this system that are essential for understanding its significance. An understanding of these attributes or premises is fundamental to an appreciation of the advantages and disadvantages of the taxonomic model as it was developed in this book. The following paragraphs make explicit some of the concepts and premises that are implicit in the model.

a. The subject matter of this taxonomy is limited to the more immediate perceptual responses or phenomena. It is likely that a unified theory of cognitive processes stressing the indivisible interrelationships among various kinds of mental phenomena would have much to say for it, yet, tradition and practicality demand that certain classes of psychological processes be abstracted from the entire mental aggregate for separate study if progress is to be made in understanding how the mind works. The range of psychological topics that I considered in this volume spans only the more immediate perceptual responses to stimuli. The range of these topics is close to what Herbert Feigl has referred to as the class of "raw feels," the primitive,

initial, and immediate sensory-perceptual responses that constitute the earliest stages of mental activity following stimulus presentation.

Obviously there is a wide range of other mental processes that overlap with and border on the topics that I have chosen to emphasize in this book. It is clear that few perceptual experiences ever develop unaffected by the social, motivational, cognitive, or experiential contexts of which they certainly are a part. The assumption behind the limits that I have arbitrarily placed on the topics discussed is that these other variables can be held more or less constant within the type of experiments that are the source of the data base that is analyzed in this book. I do not believe that this limitation does too great violence to the psychobiological reality of the situation.

b. The term "phenomenon," as I use it in this book, refers to any percept, finding, observation, functional relationship, law, or other experiential descriptor of the intrapersonal mental responses produced by stimulus scenes. The awareness of red is a phenomenon, as is either the algebraic or plotted function corresponding to the dark adaptation curve. The perception of depth, of size, and the functional effects on the threshold of the manipulation of such dimensions as the wavelength of a light stimulus are all included within the rubric I have chosen to call "phenomena." Measurements of phenomena constitute the empirical data base of perceptual psychology. They are the analogs of the molecules, cells, organs, animals, and plants that make up the observational data base of the other biological sciences.

c. The term "process" refers to any transformation or integration at any of the six processing levels that acts to alter the nature of afferently flowing information in a behaviorally significant way. In the present context the mere representation (or re-representation) of some sensory message by different patterns of candidate neural codes is not the kind of perceptually significant "process" I intended to

include within this rubric.

d. Any classification schema or level theory of the sort proposed in this book is based upon the assumption that it is possible to isolate the critical levels of perceptual processing by appropriate experimental procedures. The idea that process isolatability is achievable is a major premise of the metatheory of visual perception presented here. Without such empirical separability the levels are a priori meaningless and the categorized processes mythical. Process isolatability is clearly an essential premise in this model. The practical degree to which different level processes can be isolated from each other, depends upon experimental task and design. Many experiments are intrinsically incapable of selectively measuring the effects of a single processing level. Rather, they may record responses that reflect the influence of multiple levels of perceptual processing.

e. The fact that a particular phenomenon is affected by a process at a given level does not mean that the percept or phenomenon may not be represented or affected in other ways at either prior or subsequent levels. The underlying assumption of levels of this taxonomy, therefore, means only that each phenomenon is influenced by a critical process in the multilevel hierarchy, but it does not mean that it loses its sensitivity to influence at any other level. Neural signs of all visual perceptual phenomena are present at all levels; however, not all levels contribute to the essential informationally significant transformations that are responsible for one or another aspect of visual perception. Some nonessential levels simply passively pass on the incident information or recode it in a trivial way that maintains the pattern of communicated information as it was encoded at earlier stages even though in a different language.

A further corollary of this premise is that processes at multiple levels may affect a given phenomenon either redundantly or summatively. Thus, it is further

possible, within the framework of this schema, that identical (or indistinguishable) perceptual effects may be produced by processes occurring at several different levels. There are many instances of the considerable redundancy built into the perceptual system. For example, limits on visual acuity may be produced by non-neural effects of image degradation due to the optics of the eye, the size, the size of the retinal mosaic defined by the cross section of the individual rods and cones, as well as the convergent neural interactions in the retina. By far the most difficult area of redundant processes is that including temporal interactions among stimuli. The difficulties in isolating processes are so great in this case that I avoided them entirely and have discussed such temporal processes collectively in Chapter 7.

f. The level hypothesis embodied in this proposed taxonomic theory is based upon a system of sequential thresholds. Below the threshold for a given level, the relevant critical processes cannot begin to operate and the response of the system is totally defined by the lower level. After the threshold for a given level has been exceeded, however, the processes at the lower level are presumed to be functionally constant. This does not mean that activity at that lower level is totally inconsequential. Quite to the contrary, that prior level's function must always be continued for the phenomenon to be maintained. The point is that once having crossed a threshold for a higher level, the significance of the activity of the lower levels should only be considered to be constant but not null. It is as if the processing at the lower levels has achieved a kind of saturation of significance or meaning and while any further modulation of the codes or representations of the signal flow could occur, they would be without functional (i.e., perceptual) impact. This saturation of information is analogous to the saturation occurring in receptors in which increasing stimulus intensity finally arrives at a level at which the receptor is no longer able to respond more robustly. In the case of information saturation, no further alteration

in the meaning of the encoded message occurs, even though the dimensions of the coded signals may still be changing. Over a certain range of the signal, all variations mean exactly the same thing.

g. The proposed hierarchy of levels is uniquely linked to anatomic levels only at the first two levels. The third level is equivocally neural while the fourth and fifth are patently psychological and descriptive models beyond any hope or promise of neurophysiological reductionism. Thus, the whole schema of a hierarchical series of processing levels proposed here is a mixed and eclectic psychological and neurophysiological metatheory of perception.

h. It is likely that only the processes incorporated into the first three levels of this schema need maintain any semblance of isomorphic representation. Beyond the third level, symbolic and nonisomorphic representation, a host of experiments tell us, is probably more likely.

i. A vitally important premise of this multilevel theory is that the hierarchical scheme of levels proposed here is a taxonomy of processes and not directly of phenomena. Although many phenomena will be closely, and in some cases uniquely, linked to particular levels, the taxonomy is of processes operating at each level and not of the phenomena themselves.

j. The terms "symbolic", "interpretive," "inferential," "constructionistic," and "rationalistic" all are used as interchangeable synonyms in developing this taxonomy. Although the denotation of these terms is difficult to express precisely, they all refer to highly complex and nonlinear neural network computations by means of which responses can be generated that are not predictable in terms of the passive, linear, or deterministic transformations typical of simpler nets. Since we cannot presently understand how these processes work at the microstructural level, we are obligated to study them at the overall molar level.

This then, in very broad outline, is the set of premises and assumptions upon which this project was based. This final report is, in fact, only a brief abstract of the book that has now been drafted.

To more completely outline the progress that I did make during the course of this contract, in the next two sections I present a summary of each chapter and then the total text of Chapter 12--the epilog to the book in which the emerging principles of preattentive, automatic visual processing are summarized and tabulated.

II. SUMMARIES OF CHAPTERS

Chapter 1 introduces the general problem area of this book. In addition to spelling out the metaphysical and epistemological issues that constitute perceptual science, it also attempts to define what is meant by the word "perception." An important part of this introductory chapter is the groundwork that is laid for an eclectic approach that involves both neoempiricistic and neorationalistic concepts. The bulk of Chapter 1, however, is a statement of the major intellectual and scientific questions towards which the energies of perceptual scientists are directed. Unfortunately, few of these questions are answered by the end of the book. Nevertheless it must be appreciated that it is this set of relatively high level and philosophical questions that provides the main motivation for the best research in this field, not the more mundane issues that surround each individual experiment.

Chapter 2 is an historic review of previous metatheories of perception. In this chapter the dichotomy of the two classic schools of thought (empiricism and rationalism) is made clearer and an effort is made to clasisify and organize the theories themselves. Three dimensions are proposed as discriminada for perceptual theories; these dimensions represent the range of possible positions taken with regard to the three great questions of perceptual science. (A) Is perception innate

or learned? (B) Is perception local or global? (C) Is perception direct or logically mediated? A discussion is also presented of the role of theory and of the plausibility of adequate theories in perceptual science.

Chapter 3 surveys a variety of technical topics that are necessary background material for perceptual theory and experimentation. The epistemological question--How do we gain knowledge about external reality?--is meaningful, of course, only in the context of some statement of what external reality is. Similarly, the nature of physical reality at the subnuclear level is fundamental for understanding the nature of electromagnetic radiation, the actual triggering stimulus for visual perception. Furthermore, the anatomy of the photoreceptors is basic to understanding the visual process and knowledge in this area is also in a state of rapid change. A review of this area, therefore, seemed timely as did a discussion of the simple optics necessary to understand image formation in the eye. Finally this section ended with a brief discussion of the psychophysical methods used in visual research with a special stress on identifying the task to which each might best be applied.

Chapter 4 is a prolog to the substantive material to follow in subsequent chapters. It is a discussion of the premises and conceptual foundations of the taxonomic metatheory that is represented by the remainder of this book. A considerable portion of this chapter was dedicated to identifying the reasons that satisfactory theory is so difficult to develop in this field. Empirical, logical, and conceptual obstacles were all identified as contributing to this less-than-satisfactory state of theoretical affairs. The major contribution of this chapter, however, was to spell out the implicit and explicit and essential concepts that were implicit in this metatheoretical effort.

Chapter 5 was the first substantive chapter and delat with Level 0 preneural transformations that were of perceptual significance. Physical modulations of the

incident light stimulus by the external environment, as well as the optics of the eyes, were discussed. A major point made in this chapter was that many "illusions" are not due to transformations in the perceptual system but were really "mirages" due to attenuation and aberration of light by pretransductive processes that did not involve the conversion of energy away from the photic form in which it was emitted or reflected by the distal stimulus object.

Chapter 6 dealt with the first specifically perceptual stage of transformation (Level 1) occurring in the receptors. Even in this single cell, significant changes in the significance of the incoming signal can occur. In general, we are very knowledgeable about the chemistry and neurophysiology underlying these perceptually significant receptor transformations. Aspects of perception such as the absolute threshold or trichromatic color addition could be specifically associated with the quantum physics of photon absorption. Suprathreshold amplitude functions seemed, on the other hand, to be attributable to the physiology of neural mechanisms deeper in the receptor cell.

Chapter 7 was a multilevel digression. As I surveyed the literature of temporal processes it became clear that this area was one of the instances in which it was not, in fact, possible to totally isolate the levels of processing. For reasons that were spelled out in detail in that chapter, it is not possible to distinguish Level 1 and Level 2 contributions to many temporal interactions. A wide variety of phenomena had to be considered that could only be ambiguously assigned to latency, prolongation, and sequential interactions of the neural responses at either Level 1 or Level 2. Thus, for example, while neural latency affected a number of perceptual phenomena, it was not, in principle, possible to segregate the persistent effects in the receptor from functionally redundant effects in the neural networks. Many previously unrelated temporal phenomena were also discerned as being the result of

response prolongation possibly occurring at both levels. This synthesis was an example of an important result of this project.

Chapter 8 dealt with the function of relatively simple networks of neurons. Here the neurophysiology and chemistry of the individual cell was not as important as the design of the network into which it was connected. Not surprisingly, there was a predominance of spatial effects here (since the neural network is a spatial concept) but there were also temporal effects that were specified by the sequence of spatial states into which the network fell. Convergence, lateral interactions, and more complicated recodings were all found to underlie a wide variety of perceptual phenomena.

Chapter 9 was a continuation of the conceptual analysis that had begun in the prolog of Chapter 4. This mezzolog was a critique of current neuroreductionism and a consideration of the limits of this important means of theoretical analysis. An attempt was made to clarify some of the vocabulary of neuroreductionism and to spell out the specific assumptions and premises of four standard theoretical approaches. The major contribution of the chapter, however, was a survey of the various dogmas that seem to have wide currency in the field today and the enumeration of empirical counterindications (heresies) to these dogmas. In general, it was concluded that neuroreductionism, while seductively attractive, is not as broadly applicable as is now widely believed. The limit of neuroreductionism is the boundary at which the neorationalistic, constructionistic, inferential vocabulary, and research methodology becomes dominant over the neoempiricistic approaches. This chapter established the conceptual foundation for that transition and the need for the eclectic taxonomy

Chapter 10 was a discussion of Level 3--the level of perceptual processing

mainly involved in the organization of figural percepts. It is here that neuroreductionism first fails completely and descriptive analysis becomes predominant. Factors affecting the organization of figure and ground were considered, including the quasistatistical analysis of the global properties of textured fields and the classic studies of surface cues to figure-ground segregation. A second major theme was the nature of unstable visual perception caused by ambiguous cues--fading and reversal being the dominant effects considered in this part of the discussion. In general, it was shown that there is a substantial body of empirical data showing that there are many (Level 3) perceptual processes that probably depend only upon a single dimension of the stimulus to produce a qualitative organization of the visual field.

Chapter 11, on the other hand, dealt with processes that involve multiple dimensions of the stimulus. It was only in such instances, it was asserted, that quantitative experience was possible. We might be able to discriminate between two colors on the basis of Level 3 processes, but the Level 4 processes described in this chapter depend upon integration of multiple aspects of the stimuli if the observer is to be able to report anything about the actual color experience (or the depth, extent, magnitude, or duration of the response to any other stimulus). This suggested that quantitative dimensions of perceptual experience are dependent upon some kind of a relational or comparative evaluation. Many of the contrast, constancy, and stereoscopic phenomena so familiar in the perceptual literature were shown to be united by this concept of perceptual relativity.

Finally, Chapter 12, was a statement of the collective impact of the material discussed in previous chapters. Since this chapter, along with the proposed taxonomy was the intended goal of this book, it is presented in full in the following section.

III. EMERGING PRINCIPLES OF VISUAL PROCESSING

A. INTRODUCTION

This book opened with the question--How do humans acquire information about the external world? This all-too-general query was quickly particularlized to the more limited topic of visual perception and to a series of questions of somewhat greater specificity. It would be most satisfying if I were able to close this book with a summary chapter that answered the questions that I posed in Chapter 1. Unfortunately, this is not to be; even the least astute reader of this book must have been aware from the very beginning that this was to be the case. Those questions constitute the skeleton of a program of inquiry that has hardly begun. Disappointingly, I must acknowledge that, as yet, there is no grand metatheory of the more automatic, preattentive aspects of visual perception any more than there is of its active and attentive components and that this book filled the great need for a global "explanation" of perception no better than any of its predecessors.

What this book offers instead is an organizing taxonomy of visual processes and a set of general conclusions as to where we are today in our attack on the many problems of visual perception. A satisfactory, process-oriented taxonomy, I am convinced, is a necessary antecedent to any comprehensive metatheory. Nevertheless, the development of such a classification system has not been of sufficient concern to the perceptual community in the past few decades. The empirical data have currently accumulated to such a point that any further postponement of such an effort can only lead to a collapse of the entire scholarly-scientific enterprise as a result of an acute information overload. Regardless of what I may or may not have accomplished in this book, it is clear that systematization and generalization are the only plausible solutions to this problem. It is equally obvious that no information

retrieval system could solve the problem created by the glut of disorganized research reports in this active field of research. Even a modestly effective information retrieval system would simply exascerbate the problem rather than alleviate it. The only solution to the information overload created by the data explosion in modern scientific psychology is the construction of a conceptual superstructure--in other words, first a taxonomy and then a metatheory--that orders and systematizes the material so that the intrinsic patterns of organization are made apparent. After all, individual experiments are inconsequential; the general principles, of which they are but exemplars, are what really matter in the historical course of science.

The proposed taxonomy has already been presented in several ways in this book; it is presented in brief outline form in Chapter 4 and in an even more abstract and diagramatic form in Table I. However, by far the most complete outline of the proposed taxomony is the entire table of contents of this book. The table and the discussions presented in Chapters 5, 6, 7, 10, and 11 represent a detailed statement of my view of a satisfactory taxonomy of the first five levels (0, 1, 2, 3, 4) of perceptual processing. Chapter 8, of course, is an important adjunct; it acknowledges that certain temporal processes cannot be isolated in any way that would allow them to be classified within the levels of the taxonomy.

At the outset of this epilog, I should also acknowledge that I do not believe that this particular taxonomy will either be fully accepted initially or preserved intact very long by my perceptual science colleagues. There were, without doubt, certain arbitrary criteria applied in developing this classification system that some will find less than fully satisfactory. Some levels of analysis are probably more robust than others; I do not believe that anyone could dispute the fact that there are external, preneural, Level 0 processes that influence visual perception. On the other

hand, as I progressed deeper to the more central levels of perceptual processing, I became increasingly skeptical that the particular criteria that I had chosen to discriminate between levels were the only satisfactory ones. Frankly, it would not take too much of an effort for someone to convince me that Levels 3 and 4 should have been organized in accord with criteria other than those of unidimensional figural organization and multidimensional quantification that I chose. I think the main reason for this uncertainty is the fact that these more central processes are, in fact, not well understood and, as yet, no natural criteria comparable to the neuroanatomical and physical links have yet appeared. On the other hand, I am equally convinced that I have used acceptable, if not unique, criteria and that any other selection would have been either equivalent or subject to the same uncertainties.

There is one general criterion, however, to which I am still deeply committed; that criterion is that the main basis of any satisfactory perceptual taxonomy must be underlying process rather than experienced phenomenon. To classify on the basis of phenomena, as have most texts and other analyses of the field of visual perception in the past, is tantamount to confusion from the outset. I hope that this book has established that a hierarchy of processing levels is the most orderly dimension along which a taxonomy of visual perception can be constructed. It is this single point--the inappropriate choice of the criterion of phenomenon rather than of process--that by itself may be responsible for much of the chaos that typifies so much of the summarizing literature on visual perception. Using process rather than phenomena was the key that helped me to personally unravel the tangle of the empirical literature. It may be an illusion, but I feel that I can, now at least, see some pattern to that chaos and can much more easily understand where a newly encountered experiment fits into the grand scheme of this science. It is my hope

that this taxonomy will also serve a similar function for my readers; that, indeed, is the major contribution I hope this book will make.

The main purpose of the epilog to this book, therefore, is to broadly survey what has been discussed in detail in previous chapters and to extract a list of generalizations that represent the collective implications of this topic as an integrated science rather than the specific details of individual experiments. We seem often to forget the meaning of the method of detail. We do not do well controlled univariate experiments for their own sake. The reason we carry out these sometimes silly experiments (which exist in a microcosm that is so terribly isolated from complex reality) is a practical one; multidimensional reality makes it logistically difficult to describe what is happening when several variables are simultaneously varying. The impact of each study, no matter how abstract the experimental situation, has to be measured in terms of what it contributes to the overall perspective, not what it says in isolation. If one accepts this statement, it is *obligatory that some conscious effort be made to extract those broader implications.* In this epilog, I list, without further argument or citation, the major emerging principles of perceptual research as I see them at the conclusion of my studies. This dogmatic approach, which I have used in the two preceding books in this series (Uttal, 1973 and 1978), is of course, a highly personal evaluation, but I do not believe that it is aberrantly idiosyncratic. In my opinion, and that of many of the perceptual psychologists who have influenced me, this is the state of perceptual science at the present time. Though there may be disagreement concerning specific issues or conclusions, the resulting overall metatheory is one with which I am sure most of my colleagues would not find too great difficulty in accepting.

In this epilog, I distinguish between two levels of emerging principle--the metaprinciple and the general principle. The metaprinciple makes a statement that

extends across many issues and describes a global aspect of perception. As its name suggests, it is a major organizing conclusion that encompasses many of the less "general" principles themselves. Metaprinciples are the great organizing universals that emerge when one studies visual perception and reflect the tenets of a global epistemology of visual knowledge acquisition. The "general" principle, on the other hand, while transcending the conclusions of an individual experiment is not intended to be quite so universal; it speaks more to the data level than to the level of global doctrine. I make no attempt in this epilog to summarize detailed conclusions concerning the effect of some independent variable on some dependent variable; that task, I hope, was accomplished in the text of the preceding chapters, the many detailed discussions of individual experiments, and the lists of findings that I presented therein.

B. METAPRINCIPLES OF VISUAL PERCEPTION

The following metaprinciples represent the doctrines and canons of a modern perceptual epistemology. Implicit or explicit, I believe that they can be identified in the thinking of many contemporary perceptual scientists. What follows in this section is, in fact, a perceptual credo.

1. Materialistic Realism

Perceptual psychologists consider the external world to be real in the sense that it does not need to be perceived to exist. Pragmatic concerns dictate that the internal perceptual state must be referenced or anchored to the external physical state merely because the latter is measured in less ambiguous and more consistent terms than other perceived stimuli.

2. Psychobiological Monism

Percepts and other perceptual responses are also real in that, in principle,

some neural state must be identifiable with every mental response. No matter how inadequate contemporary neuroreductionistic models may be (the reader should be well aware of my biases in this regard at this point) this should not detract from the fundamental metaphysical premise that mind is based upon the brain--solely, uniquely, and irrefutably. The only foundation for mental process is the neural substrate and without the brain, mental process ceases. Mind is but one aspect of the neural function of the brain; the two are inseparable.

I restate this metaphysical metaprinciple at this point to make absolutely certain that there be no misunderstanding that my rejection of neurophysiological models of some perceptual processes is also a rejection of the radical, materialistic, physicalistic, and realistic monism implicit in the psychobiological approach to the study of mental processes.

3. Methodological Dualism

In spite of my conviction that a radical metaphysical monism is basic to any modern perceptual metatheory, the survey of data and theory presented in this volume has also made it clear that such a metaprinciple cannot be applied in most practical situations. The links between neurophysiology and perception are, for the most part, unknown and the complexity of the neural networks that must be involved in even the simplest percepts is often so great as to preclude any reductionistic analysis. Intrapersonal mind is not directly examinable; only interpersonally communicated behavior. Thus, a modern perceptual metatheory or taxonomy must be methodologically dualistic; i.e., it must invoke concepts, methods, and elements from both the neural domain and from a molar domain that is patently nonreductionistic. It must, in other words, be dualistic in its methodology. Again, it must be emphasized that this is a practical and epistemological consideration and does not mitigate the psychobiological monism that should take precedence in one's

metaphysics. The end result of this methodological dualism is that any taxonomy or theory of perception making any claim to comprehensiveness must be an eclectic one. Physical, neural, and rational transformations must all be invoked to explain the full range of perceptual phenomena; the perceiving mind must be dealt with as if it were an active, inferential, constructionistic engine in at least part of any metatheory.

Empirical evidence is beginning to accumulate that tends to show that both low level deterministic neural and high level inferential processes can exert similar effects. Bekesy's invocation of Mach and Hering types of lateral interaction and Braddick's concept of a dual mode of motion detection are contemporary indications of the necessity of invoking both neural and constructionistic processes in perceptual explanation. Once again, however, I must note that the fact that we must treat the mind, in at least some cases, as an inferring, constructing, symbolizing, interpreting engine, does not mean that mind is in any way substantially different in kind than the brain. It only means that the mechanisms underlying those particular high level processes are beyond our means of analysis, both currently and possibly in the future. Rationalism, like statistical mechanics, is a molar expedient that is used when one is faced with enormous complexity or numerosity. Though complex, a rational machine is no less deterministic or empiricistic, in principle, than a simpler one.

4. Multilevel Processing

An equally important emerging metaprinciple asserts that perception is the result of transformations that occur at many different levels of processing. I have identified six levels, and it seems evident that each is capable of influencing some aspect of quality, quantity, extent, or duration of the mental responses to external stimulus patterns we call percepts. The implications of this multilevel meta-

principle go far beyond the mere organization of this book. This metaprinciple implies further that there are many opportunities for any aspect of the afferent stimulus information to be transformed. The phenomena of color, for example, cannot be solely attributed to transformations at any single level even though the processes that occur at each level can be so localized. This means that explanations and theories of perception can neither be limited to peripheral nor central factors alone. Eclectic theory thus reflects the intrinsic biological nature of the process and is not just a taxonomic convenience.

A corollary of this metaprinciple is that since all percepts are multidimensionally caused, (i.e., all percepts result from the impact of many dimensions of past and present stimulus scenes), no unidimensional psychophysical law is valid except as the roughest of approximations in a highly abnormal situation.

5. Invisible Invariance Computations

Many of the high level processes that have been described in this book involve the extraction of information or invariances that exist only in terms of the differences that exist between two or more dimensions, presentations, or transformations of the stimulus. The mental computations that must be carried out in order to construct percepts from stimuli in which the information is not explicit are themselves extremely elusive objects of scientific inquiry for two reasons. First, they are invisible to the perceiver who is aware only of the outcome of the process and not the process. Second, the process is never directly open to interpersonal examination. Thus the nature of the process must, in general, be inferred from the outcome of the process. As I have noted in the text of this book, this latter limitation is a severe restriction under which to search for the characteristics of a putative internal mechanism; many (in fact, an infinite number of) analogous mechanisms can produce the same outcome. It is also for this latter reason that the

application of mathematics to perceptual analysis is inherently indeterminate. Mathematical theory, in much the same way as behavior, is intrinsically incapable of uniquely specifying the internal structure of a "black box." I cannot stress too strongly, however, that this restriction is not special to psychology. The invisibility of the objects of inquiry is just as common in many other sciences, including the most macroscopic (astronomy) and the most microscopic (basic particle physics) as it is in psychology. These sciences also must make inferences about the nature of their own invisible reality on the basis of indirect evidence. Their theories can also only be tested for plausibility and consistency; the mathematical models of physics are no more susceptible to tests of exclusive validity than are those of psychology. On the other hand, psychology is no less susceptible to scientific analysis than are any of the simpler sciences.

6. No Need for Isomorphic Representation

Throughout this book, as well as in the literature of sensory coding mechanisms in the peripheral nervous system, there is ample evidence that any dimension of the stimulus or percept may be represented by any dimension of the neural response. The efficacy of symbolic and quasicognitive factors in altering the percept is also well demonstrated at the higher levels of perceptual processing. The impact of all of these data is to stress that there need not be a "toy in the head" for there to be a "picture in the mind"; that stimulus-neural response-perceptual isomorphism is not necessary for the representation of mental experience. Even spatial concepts can be suggested by stimuli in a way that is so compelling that it is often hard to distinguish between the inferred subjective surface or contour and the response to a stimulus that is actually physically present. Stereoscopic space need not be represented by a three dimensional array of neural circuits in the brain--it is equally well represented, according to this

metaprinciple, by a sequence of printed symbols such as c-u-b-e or by an equivalent set of highly transformed neural symbols. Lord Adrain's (1928) advice to psychobiologists "Seek Isomorphisms" was simply wrong.

7. The Perceptual Indeterminancy of Stimuli

The multidimensional and inferential nature of perception makes it clear that traditional stimulus-response psychology, while a convenient expedient, also drastically misled psychological theorists in their search for the relationship between the external physical and the internal mental worlds. Percepts are not determined by stimuli but rather are cued by what are, at best, partial and incomplete hints and clues provided by the stream of afferent information in the peripheral communication pathways. Perception is, for the most part, an act of inferential construction--a mental model making of the external world on the basis of limited, but multidimensional, information. For the most part true veridicality does not really exist. The degree of veridicality that does exist is, to a large extent, fortuitous and stimulus-response determination apparent rather than real.

A corollary of this metaprinciple is that the visual system does not have a means of adequately dealing with lacunae. Ignorance (missing information) is as invisible to the perceiver as are the processes that underlie perception. As philosophers have told us for millenia, we cannot appreciate what it means to not know the unknown.

C. SOME DISAPPOINTMENTS

These, then, are the major metaprinciples that have emerged during the writing of this book. All of these doctrines are essentially positive and reflect some kind of a conclusion to which I was directed by the press of the data. It

would be incomplete, however, if I did not acknowledge that there were some disappointments in carrying out this research--some questions that I posed to which neither I nor anyone else seems to have found a satisfactory closure. Even worse, some of these dissapointments reflect fundamental uncertainties concerning the possibilities of progress in the immediate future. The following list tabulates some of these disappointments.

1. The Failure of Neuroreductionism

Despite my personal theoretical predilections to the contrary, there is no escaping the fact that neurophysiology does not provide an adequate model for most aspects of perception. Nor is there any resisting the argument that is inherent in the data summarized in Chapters 9, 10, and 11; in general, current neural models are less robust than their originators have often acknowledged. In fact, many neural models are so remotely linked to perceptual phenomena that they purport to explain that they must be considered to be no more than distant physical analogies. The line demarcating the physiologically explicable from the inexplicable moved to ever lower levels as I proceeded through the task of developing the taxonomy; I have placed many more processes at Level 3 or 4 than I thought I would have at the outset of this project. As a result, like most other perceptual scientists, I was required to shift to the nonreductionistic and neorationalistic vocabulary that I invoked at the outset of this book. Words like symbolic, inferential, constructionstic, and interpretive had to be used to discuss the higher levels of perceptual processing.

It is worthwhile to consider what is meant by these terms. All of them, more or less synonymously, denote molar mental processes. Their use is required, not because the underlying neural mechanisms are not real and do not exist, but because of the complexity of those mechanisms. These terms, which I have used

so frequently, may be considered to be the names of "programs" implemented by the logic implicit in the unimaginably complex neural networks of the brain. They are the action algorithms of those mechanisms, in other words. These programs or action algorithms do not exist separately from that neural substrate, but as a fully determined result of it. Nevertheless, the complexities are beyond us and, despite the metaphysical identity of these molar processes and states of neural networks someplace in the brain, we may be limited for the practical and foreseeable future to this type of descriptive molar analysis. As I said, this is a major disappointment.

2. The Failure of any Theory at the Higher Levels

I must also admit to a profound disappointment with regard to the explanations that were advanced for the more central processes of visual perception surveyed in Chapters 10 and 11. What had been a vague feeling, prior to beginning my studies, became a conviction by the time that research was complete: Solid explanatory theories at these levels of processing are few and far between. It turned out that we know shockingly little about the processes underlying the powerful ability of the nervous system to integrate various aspects of a stimulus scene, to extract invariances, and to construct or infer what might be a plausible solution to the problem so posed. We saw in Chapters 10 and 11 that the internal logic remained invisible not only to the observer but also to the perceptual psychologist. Instead, heuristic physical analogies and descriptive models, not too far removed from the data themselves, dominated the "theoretical" scene. We can assume that nonisomorphic computational processes must extract invariances (the fact that we can perceive certain phenomena is an existence proof of the existence of some such process), but the nature of these processes remains almost totally obscure. Few successful efforts have been made

to directly attack the great mystery that these intrapersonal processes represent. Although descriptive microtheories abound, no general model yet exists and while a number of highly complex mathematical descriptions now have begun to appear, their ability to describe the outcome of a process greatly exceeds their ability to give deep insights into its underlying mechanisms. Often, the ability of an analogous mathematical procedure to extract invariances; just as does the perceptual system, is mistaken for an explanation of the brain's methods. The pseudoidentification of two equally successful and analogous procedures, one computational and descriptive, and one psychological, is without merit as a logical argument for the uniqueness of the descriptive model.

It is interesting to note that although the statement "investigation of this particular phenomenon may tell us something in general about visual perception" is virtually ubiquitous in the perceptual literature, very little of general interest is learned from even the most extensive description of each phenomenon. However fascinating the study of geometric illusions may be, for example, it actually tells us little more than the nature of the illusions. This is perhaps the greatest disappointment in the study of visual perception; the manifest failure of generalization from the huge amount of data now available. It is also a major reason behind the development of a taxonomy of perceptions.

3. The Vast Areas of Ignorance in Perceptual Science.

Despite the enormous amount of empirical research in perceptual science, it is shocking how profound our ignorance is in certain areas of this important scientific area. There are five major distinguishable areas of ignorance. First, as I developed in Chapter 9, we know very little about the links between the neurophysiological mechanisms and perceptual processes. How the action of a neuronal net, however complex, can be transformed into a conscious experience is

as much a mystery now as it was in the days prior to the development of the ultrasophisticated electrophysiological research technology of which we are all so proud today.

Second, we know so very little about the nature of the suppression of the meaning of a stimulus, or its antithesis, the attribution of perceptual reality and significance to a stimulus that is only suggested but is not physically present. How can we utilize the information in a stimulus without "seeing it"? How do we see "subjective" contours?

Third, what is the nature of the attentive, conscious and willful manipulations that occur in what I have designated as Level 5 processes but have not discussed in this book. We are not only ignorant, in general, of the processes themselves, but also why these Level 5 manipulations have such a minimal effect on the more automatic processes of the lower five levels.

Fourth, though perceptual science is well aware of the many interactions that occur between various aspects of the stimulus scene, there have been relatively few systematic programs in which multidimensional interactions were the main object of study. The major empirical effort up to now has been characterized by a paradigm in which all except one variable are held constant and the effect of that one then determined. We still know very little about the mechanisms and processes by means of which multiple dimensions are integrated to collectively influence the perceptual outcome.

Fifth and finally, we know very little about the nature of the internal mental algorithms that actually extract invariances from temporal or spatial arrays of stimuli. While we can simulate these mechanisms with analogous processes, we have no means yet of determining what is actually going on when these elaborate computations are carried out.

4. The Irresolvability of the Issue of the Plausibility of Perceptual Theory

Finally, I think one of the major disappointments in this work is that I have not been able to provide even a preliminary answer to the question of the plausibility of ever developing a theory of visual perception that is satisfactorily explanatory, reductionistic (in the sense that terms at one level are defined in terms of a lower (neurophysiological or otherwise), and comprehensive. The issue of the possibility of ultimate success of a research effort is a dreary one since it can be interpreted as nothing more than a pessimistic and discouraged response to the state of the science at present rather than a valid epistemological inquiry. The question raises doubts about the future and can always be countered with optimistic hope--an attitude with which I, like most people, would personally prefer to embody in my own philosophy. The question is even more distressing when it is not answered, but the issue of the limits of our scientific knowledge is valid and it must be asked particularly in light of some of the modern developments in logic and mathematics. After all, the Heisenberg uncertainty principle and the speed of light represent physical limits; a unified perceptual theory may be equally impossible because of similar limits on practical computability or because of the logical difficulties expressed by Gödel's theorem. Regardless of whether perceptual theory is ultimately possible or not, the absence of an answer to the question itself is a major disappointment.

D. GENERAL PRINCIPLES

So far I have tabulated the broad positive metaprinciples of perceptual theory and some of the major negative disappointments that have emerged during the course of this project. There is also a set of somewhat more specific conclusions or precepts that represent a much more detailed view of the meaning

of the vast body of perceptual data now available. In the following list, these "general" principles are dogmatically stated as specific examples of the progress perceptual science has made and as an expression of my own personal view of the contemporary status of the field. Justification for each of these dogmas (or in some cases heresies) will have to be found in the preceding chapters; their presentation here is without further support. I hope that these principles will help readers in establishing their own viewpoints whether their responses are agreement or rejection of each of the individual principles.*

1. Perception is defined as the relatively immediate, intrapersonal, mental response evoked as a partial, but not exclusive, result of impinging multidimensional stimuli, as modulated by the transforms imposed by the neural communication system, previous experience and contextual reasonableness. Each percept is the conscious end product of both simple algorithmic transformations and more complex constructionistic "interpretations". However, the underlying neural and symbolic processes are not part of the observer's awareness.

2. Visual perception, in large part, is an active process dependent upon global properties, multiple dimensions, and the state of the perceiver. Percepts are solutions to the problems posed by the environment and involve processes that give rise to reasonable and plausible models of the external world. They are not passively determined responses to prepotent single stimulus dimensions.

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*This list of general principles, though more extensive than other previous attempts to tabulate perceptual wisdom is not unique. Readers who would like to consider other points of view will find examples of similar tabular summaries in Gregory's (1974) chapter in Volume I of Carterette's and Friedman's Handbook of Perception and in Rock's (1975) text.

3. Relationships are exceedingly important, not only in terms of the interactions between different parts of the stimulus, but also in terms of the relative amount of activity in coded neurons. Percepts in space and time are all "relativistic" in this sense. When only a single dimension or code is available, and no relational comparisons are possible, the result is usually a nonquantitative and ambiguous experience.

4. For millenia there has been a deep seated urge on the part of philosophers, scientists and laymen to explain the phenomena of perception. Such explanations take the form of theories, a word that does not connote unwarranted extrapolation but rather, an integrative extension from the bare facts of individual observations to a comprehensive explanation. Theoretical integration, not the unadorned collection of facts, is the raison d'etre of science in general and of perceptual science in particular. No theory, however, has ever withstood the test of time. Theories come and go along with the prevailing technology and scientific Zeitgeist.

5. Historically, theories of perception may be divided into two major classes; the first class includes those that are empiricistic, passive, and deterministic; the second class includes those that are rationalistic, constructionistic, interpretive, inferential, and active. Both classes are presently required to give a comprehensive explanation of visual perception.

6. Perceptual theories typically deal with a restricted universe of experimental data. As such they often do not intercommunicate and are, for the most part, highly restrictive in their coverage. Macrotheories of perception, therefore, are not in general, antagonistic to each other, but in most instances, are complementary and/or supplementary.

7. The major characteristics of any macrotheory of perception can be characterized by its position in a three dimensional query space which depicts the stance of each theory's response to three great questions: (a) Is perception mainly innate or mainly learned? (b) Is perception mainly empiricistic or mainly rationalistic? and (c) Is perception holistic or elementalistic?

8. There is a wide variety of empirical, logical, and conceptual obstacles to theory development in perceptual psychology. An appreciation of the nature of these obstacles makes it easier to understand why the search for satisfactory explanation has been so difficult. The only practical response to these difficulties at present is a multilevel, eclectic, taxonomic theory of the kind presented in this book. In fact, this is the consensus; no alternatives exist and all perceptual metatheoreticians are implicitly or explicitly multilevel and eclectic, if not taxonomic in their approach.

9. The key to a satisfactory taxonomic theory is the concept of the critical process--transformation that alters the information content of an afferent signal, not only in terms of the neural language in which it is encoded, but also in terms of its meaning or significance. Many processes and transformations within the nervous system are not critical in this sense but may simply be changes in code without changes in meaning. The definition of a critical process also implies the existence of an isolatable critical level at which that process occurs.

10. The notion of processing levels may say something about the constraints and transformations that the nervous system imposes on the flow of coded information but it does not say anything about the level at which psychoneural identity occurs, i.e., where the neural equivalent of a perceptual experience actually occurs.

Many studies of the nervous system show a correlation, transformation, or analysis of an afferent signal at one or another level but this does not mean that such a locus is the site of the psychoneural equivalent of the resulting percept. The fact that information is encoded at all levels does not mean that psychoneural identity between perceptual neural states exists at all levels.

11. The anatomy of the retina shows that elaborate information processing occurs in the eye, but it is unlikely that an isolated eye would be able to perceive anything. It simply modulates the incoming signal, sharpening contours (among other transformations), and removing information which is redundant (constant). Similar neural net processes occur at other levels of the visual pathway.

12. The initial photochemical reaction in vision is well understood as the isomerization of rhodopsin to the all -trans (unstable) form from the 11-cis (stable) form. All subsequent photochemical processes are thermally driven dark reactions and can follow their course without further photic stimulation. This isomerization is the "primary sensory action" in vision.

13. There appear to be multiple pathways from the eye to the brain. The lateral geniculate-cortical pathway seems to be concerned mostly with fine form perception while the collicular pathway seems to be associated with eye movements (foveation), alerting, and general orientation. As many as a dozen visual pathways are to be found in some vertebrates and there are many cortical areas in the mammalian brains. The functions of the various areas are not definitively known.

14. Many perceptual phenomena are wrongfully attributed to processes within this multilevel perceptual processing system when, in fact, they are the result of

highly veridical responses of the system to transformations that occur prior to the initial sensory transduction. These preneural transformations, referred to as Level 0 processes, may have colossal perceptual impact, but they do not say anything about the properties of the perceptual system. Level 0 processes may be generically referred to as mirages to contrast them with the illusions produced by nonveridical transformations within the perceptual system.

15. The first level of truly perceptual processing occurs in the receptors where physical energy from the external world is transduced and encoded into the electrochemical energies of the nervous system. Both the photochemical and neural properties of the receptor can affect perceptual experience.

16. Rushton's law of univariance, a corollary of Muller's law of specific energies is fundamental to understanding photoreceptor action. This law states that once transduced, the neural signal carries no trace of the wavelength or intensity of the stimulating photic energy.

17. The absolute energy threshold of a single receptor appears to be only that of a single quantum of light; the whole observer appears to be also sensitive to even this low level of energy. Therefore, the human visual system is as sensitive as it can possibly be in the context of modern quantum theory.

18. Temporal summation may sometimes mimic spatial summation in the retina. Both occur within limits however, leading to the postulation of such hypothetical entities as the "area of spatial summation" and "the critical duration". In fact, however, both of these entities may represent regions of interaction probability rather than sharply demarcated anatomical or temporal regions.

19. The absorption spectra of the receptor photochemicals, the state of adapta-

tion, and the availability of receptors, account for a wide variety of perceptual phenomena including the luminosity curves, trichromatic color addition, increment thresholds, and abnormal color vision. However, none of these responses is totally determined by the stimulus or the momentary state of the peripheral portion of the perceptual system, both of which can be overridden by higher levels of processing.

20. The three dimensions of the chromatic stimulus (spectral composition, spectral purity, and luminosity) all jointly affect the three dimensions of the perceptual response (hue, saturation and brightness). Thus there is no strict association between any single attribute of the stimulus and any single attribute of the chromatic response.

21. Though a fundamental limit on visual acuity is set by the size and density of the receptor mosaic, other factors, such as neural convergence, contribute to visual acuity. Hyperacuity, on the other hand, as exemplified by vernier acuity and which seems at first glance to exceed the limits set by the properties of the retinal mosaic, may result from quasistatistical processing at a considerably higher level.

22. Extreme depletion of the photochemical must occur before the threshold is affected. Since measurable effects of adaptation can be obtained at relatively low light levels (at which photochemical depletion is modest) the implication is compelling that there must be both photochemical and neural components to light and dark adaptation.

23. The suprathreshold dynamics of the function relating perceptual magnitudes and stimulus intensity appears also to result from receptor level processes. How-

ever, in this case the function is a result of the dynamic compression occurring in the neural mechanisms subsequent to the receptor's photoabsorption process.

24. While information conducted along the sensory communication channels does not entirely define the percept any more than do the properties of the receptors, the characteristics of the channels also constrain and modulate what is seen and can also leave their own traces in the perceptual response.

25. Afferent neural codes and representations need not be isomorphic to the percept. This is sometimes forgotten when dealing with forms in which there is a natural isomorphism in the peripheral portions of the system. However, colors are certainly not coded by isomorphic representations and this disassociation raises doubts about the necessity of isomorphism where it does fortuitously occur. The ubiquitous disassociations of percept and code found elsewhere strongly suggest that all experiences can be represented by nonisomorphically encoded stimuli.

26. Current neuroreductionistic theories of "perception" probably better describe the properties and capabilities of the peripheral communication network than the more central sites of integration and psychoneural equivalence.

27. All psychophysical tests measure two kinds of processes (a) the sensory or discriminatory processes; and (b) the criterion selection processes. Superimposed on the determinations of sensory limits are the criteria applied by the observer to determine what will be accepted as a valid stimulus. Signal detection theory analyses are unique in that they tease these two processes apart in a way that allows them to be independently measured. Forced choice experimental design minimizes the criteria effects.

28. Perceptual time displays some peculiar qualities. It apparently is not always

processed in the same way as external clock time. Phenomena can occur in reverse order to stimuli. For example, apparent motion occurs in a direction that is defined by the "awareness" of where a second stimulus is but well before that stimulus is "perceived." We clearly do not yet understand the relation between psychological and physical time.

29. It is extremely difficult to attribute temporal processes to a particular level of processing because of a fundamental difficulty, namely that receptor (Level 1) and neural network (Level 2) processes may either be redundant or, though produced at the receptor level, indistinguishably exhibited at both levels.

30. In general, the neural and perceptual responses to even the briefest stimulus are substantially prolonged. The prolongation is progressive as the signal ascends the afferent pathways and more and more neurons are involved. Many perceptual effects can be directly attributed to this prolongation of the neural response. Most obvious examples include a decline in temporal resolvability, an increase in apparent duration, afterimages, iconic storage, and temporal summation.

31. Other perceptual phenomena such as the elongation of reaction times with decreased stimulus intensities and the Pulfrich effect seem to be attributable to variations in the latency of the peripheral neural response.

32. Several distinguishable classes of visual masking exist. Though examined in the context of a single experimental paradigm--sequential presentation--the various kinds of masking arise from vastly different underlying processes scattered through all levels of the perceptual system. The main classes of masking are:

1. Bright flash masking

2. Camouflage as a result of figural summation

3. Signal diminution as a result of lateral inhibitory interaction

4. Textural masking

5. Masking as a result of gestalt grouping

6. Metacontrast

A considerable amount of confusion exists in the perceptual literature because these phenomena are not usually distinguished as the respective outcomes of different processes, but are uncritically identified with each other on the basis of the common experimental design. This is another example of the logical disorder that can result if one bases one classification of perception on phenomena or experimental design rather than the best possible judgment of underlying processes.

33. Simple neural interactive mechanisms such as convergence, divergence, and *reciprocal summatory* and inhibitory interactions represent the logical elements in the brain's computational system. It is clear that all other mental processes are generated from these simple logical elements by myriad concatenation. From one point of view, all higher level perceptual and other mental processes are Level 2 neural network interactions. Higher levels of processing, framed in the vocabulary of psychological, rationalistic, and molar terms do not deny this fundamental logical reality, only the practical difficulty of attacking the problem at this level.

34. Lateral inhibitory interactions play an important role in reducing the redundancy of the transmitted neural signal by emphasising contours. This contour intensification does modify the signal in a way that is perceptually significant. Among other phenomena, simple neural network interactions result in

such phenomena as the Mach bands and the Hermann grid.

35. Neural convergence is the proximal cause of a number of perceptual phenomena. These include spatial summation, limited spatial acuity, and color blindness in the periphery of the normal retina. Lateral inhibitory interactions appear to be the proximal causes of several kinds of spatial inhibitions including those occurring between small spots and within larger spots, and at edges, contours, and gradients.

36. Although there was some initial suggestion that each of the four kinds of photoretinal receptors interacted only with their own kind, it now seems certain that interactions occur among the four types as well as within types. Such interactive processes are necessarily implicated in the recoding that occurs as one passes from the trichromatic receptors to the opponent bipolars.

37. Other neural interaction mechanisms in the retinal plexus must also be invoked to fully explain dark adaptation and phosphenes.

38. Neural interactions leave traces in the afferent signal that affect subsequent perceptual constructions. These traces are mediated by actual alterations of the afferent sensory signal; i.e., the significance of the information is changed; it is not just recoded by these transformations. These neural interaction processes are the prototypes of the deterministic, passive, empiricistic actions that occur in the perceptual system.

39. Though a wide variety of neuroreductionistic explanations of other perceptual phenomena have been based on the same neural interaction concepts to which I have just alluded, in fact, there is an abundance of evidence that many of these models exhibit only the loosest kind of physical analogy with perceptual processes.

These analogies are based only upon similarities of form; they are often devoid of the solid empirical and conceptual links required for a definitive explanation of perceptual performance. Many phenomena, often attributed to simple neural interactions, exhibit properties totally inconsistent with such an approach. A wide variety of empirical counter indications denude many neuroreductionistic "dogma" of any validity. This has led to some counterdogma (or heresies) that are becoming increasingly palatable to an ever larger number of perceptual scientists.

40. A modern metaphysical monism must accept the facts that the proximal cause of most perceptual phenomena is the state of activity in a very large number of neurons and that the statistics of these networks is so complex as to require a molar and rationalistic approach to most of the problems of perceptual science. In perceptually significant neural networks, no neuron is uniquely necessary and most neurons probably are involved simultaneously in many processes. For these reasons, as well as simple numerosity, real neural networks probably must be classified as intrinsically noncomputable problems even though they are formally finite.

41. Though neural nets may simulate continuous field processes and action at a distance because of their small size and great numerosity, the fundamental logical manipulation in such nets is discrete and only locally interactive.

42. The higher levels of perceptual processing are characterized by a lack of linear veridicality: i.e., there is a substantial tendency for the perceptual responses not to replicate independently obtained estimates of the dimensions of the stimulus array. This may be reflected in a total dissociation of the perceptual dimension from the stimulus dimension with which, *a priori*, it would have been expected to have been most closely related.

43. Level 3 processes seem to represent a qualitative stage of processing that must occur prior to Level 4 processes. However, the idea of a sequence of perceptual processing from Level 3 to Level 4 is not clear cut; both levels may occur simultaneously or in a way in which order does not matter. Nevertheless the key phenomenal outcome of a Level 3 process is the qualitative segregation of the component parts of a complex scene and the organization of those parts into, among other formats, figure and ground.

44. Both surface cues (textural and chromatic properties) and contours can help to segregate areas of a visual scene.

45. The human observer seems to be able to process the statistical properties of a texture only up to the second order. While differences in density (first order statistics) and distribution eveness (second order statistics) seem to be quite discriminable, in only a few exceptional cases can difference in third order statistics be discriminated. The fact that our language has no simple words like density and eveness to describe third order statistics is another indication that we can not intuitively (perceptually) process these properties.

46. Both textural gradients and stimulus motion (vis a vis the retina) seem to be necessary for continued operation of the visual system. For reasons that probably span several levels of processing, retinal images that are stabilized in either time or in texture quickly (in a few seconds) fade away.

47. Regularities and periodicities of organization seem to be powerful cues for extracting patterns from irregular backgrounds even when the patterns and the background are composed of identical elements.

48. Monocular stimuli that are ambiguous or dichoptic stimuli which are

different tend to be alternatively perceived. The rate of reversal depends upon many different factors that clearly have nothing to do with any simple neural network type of inhibitory interaction or the physical properties of the stimulus.

49. Elements of a figure tend to be organized as described by the classic Gestalt laws of grouping. We have no idea what processes and mechanisms mediate these organizational actions. In general, however, the "better" the figure, the easier it is perceived or remembered. There is a gradual tendency for figures to improve in "goodness" the longer they reside in memory.

50. Many compelling percepts can be generated from very incomplete stimuli as a result of constructionistic processes sensitive to "suggestions" made by other portions of the stimulus. Perceptual filling, closure, and subjective contours and surfaces all represent percepts that go beyond the information explicitly carried by the stimulus. The extraordinary fact is that the processes underlying these constructs can themselves exert powerful influence on other perceptual processes. For example, a subjectively generated contour can often mask or inhibit a real contour equally as well as can a real contour.

51. Many figural organization processes demonstrate a remarkable insensitivity to the physical properties of the stimulus. Familiarity with the stimuli is typically a stronger cue for rivalry and reversal, for example, than is stimulus luminance. The physical attributes of the stimuli seem to have become informationally saturated long before Levels 3 and 4.

52. Impossible figures are not impossible to perceive. Rather, these examples of figures in which there is a clash of cues produce specific and well defined reversals as the observer selectively attends to the respective inconsistent parts.

In general, the perception is quite veridical with whatever part of the paradoxical stimulus is being attended to.

53. All Level 3 and Level 4 processes reflect the ability of the perceptual system to perform complex analysis and to extract invariances by carrying out complex computations. However, the nature of the logical steps by which these computations are carried out remains obscure. By no stretch of the imagination does a simulation of such computations (in an artificial intelligence experiment) provide a definitive description of the algorithm used by the brain. In fact, there is an infinite number of possible algorithms, all of which can effectively extract the same invariances with greater or lesser efficiency. Such simulations only test the plausibility of one of that infinite number of possibilities. However, careful simulations can highlight the general nature of the task and specifically identify certain processing steps that must be achieved to extract the invariances.

54. Quantitative experience of any perceptual dimension seems to depend upon relative comparisons of two or more dimensions or aspects of the stimulus scene. A single dimension is essentially ambiguous and leads to percepts that are highly uncertain and ill defined.

55. It is equally possible for there to be an inhibitory interaction between the meanings or significances of two stimuli as between two spatial patterns. Such a conclusion further implies that symbolic, rather than isomorphic, encoding is probably ubiquitous in the perceptual system.

56. In general, Level 4 spatial interactions seem to be broadly global and not to be functions of distance as are analogous Level 2 spatial interactions. Often a very minor modification of the physical stimulus such as the introduction of a

thread-like contour, can alter a percept mediated by Level 4 processes in astonishing ways. Such a result clearly argues against simple, spatial Level 2 models of such processes as simultaneous contrast.

57. In general, simplistic arithmetic laws of the form $\psi = f(S)$ are misleading and hold only in highly impoverished experimental situations.

58. Geometric visual illusions appear to be remarkably insensitive to cognitive or experiential interference, yet still exhibit many properties of interpretive construction. Many illusions of this type are intimately related to perceptual constancy and may be abortive attempts to maintain some perceptual dimension at its normative value. *Illusions may therefore, be examples of erroneous* responses emerging in situations for which the perceptual system has evolved useful mechanisms to handle other ecologically significant tasks.

59. The magnitude of many illusions depends upon the orientation of the pattern. Variations in magnitude may be enormous, with doubling or tripling of the effect occurring when the figure is horizontal or vertical compared to when it is obliquely oriented. Such a variation is totally inconsistent with any neuroanatomically identified anisotropy of the retinal plexus or any other known neural net.

60. *Perceived space is best described as being noneuclidean even though the* external stimulus environment (at the level of common experience) is Euclidean. The transformation from a parallel to a nonparallel Riemannian space leads directly to certain visual illusions and nonveridical perceptual responses. As in the macroscopic space-time described by Einsteinian general relativity, perceptual distortion is closely related to the presence of objects in the stimulus space.

61. Many cues to depth exist. Some are monocular and some are binocular. The most compelling cue is the spatial disparity that exists between the projections of images on the two retinae. All depth cues seem to involve some kind of a relative comparison.

62. Disparity driven stereopsis is explicable neither in terms of suppression nor fusion. A highly nonlinear construction based on interpretations of disparity difference comes closer to validly modeling the stereoscopic process. Unlike most other Level 4 processes, this informational (as opposed to image) fusion process now appears to have a relatively well understood neural basis.

63. Panum's fusional areas and corresponding points, concepts used to explain dichoptic stereopsis, appear to be functionally defined rather than true anatomic entities. Further evidence that this is so lies in the fact that there is no fixed threshold for stereoscopic fusion. Rather, the disparity at which dichoptic stimuli will "break away" or fuse seems to depend upon the conditions of the viewing situation.

64. The search for possible ghost images in stereoscopic perception is a search for a chimera stimulated by the mistaken idea that spatial perception must be modeled by spatially isomorphic neural models in the brain. In fact, ambiguous stimuli of this sort are resolved (as are all other ambiguous stimuli) by interpretive mechanisms that construct a single stable or quasistable perceptual state from among the plausible alternative. Ghost images do not exist except in the mind of the hyperisomorphic theorist.

65. Many kinds of temporal interactions exist that seem to transcend simple temporal recovery from satiation. The course of recovery of an aftereffect is

often contingent on the presentation of the test stimulus; the aftereffect may persist for extraordinarily long periods of time in the absence of a test. This outcome, among others, argues against any simple fatigue or satiation explanation of aftereffects of many kinds.

66. Apparent motion is not the only perceptual response possible when two stimuli are presented in quick succession. In addition to apparent motion, a gradual deformation of the first into the second stimulus may occur when the two are not identical in shape. In this case, all intermediate shapes are perceived as the first is transformed into the latter even though there is no physical correlate of any of these intermediate shapes. In general, many other Level 3 and Level 4 processes result in percepts that have no physical correlate and thus must reflect the outcome of some constructionistic or inferential processes in which the stimulus does not determine, but, rather, only influences the perceptual experience.

67. Many perceptual phenomena are affected by multiple dimensions of the stimulus. In many previous discussions it has been fashionable, though incorrect, to attribute such phenomena to the interaction between different dimensions of the perceptual response. This has been shown to be incorrect in principle. Even though apparent size, for example, may seem to be affected by apparent distance, in fact, the logic is compelling that it is actually affected by a single stimulus dimension that also influences apparent distance. In other words, there are multiple influences on a percept, not interactions between percepts. Such interresponse interaction would imply a dualism that is not palatable to modern psychobiological monisms.

These, then, are the broad general principles that have emerged in my research for this book. There are of course, many other more specific facts or relationships that were detailed in the various lists, tables and discussions in this book as well as a much larger body of knowledge that exists in the experimental literature that I was not able to review. It would be ostentatious for me to claim that either this enormous literature or the taxonomy and summary that I have presented here have really brought us very close to a solution of the great epistemological perplexity--how do we gain information about the external world? What we do now know is that perceptual science, particularly at the higher levels, is primarily a descriptive, rather than a reductive or analytic, science. Nevertheless, we must also admit that in the main, the nature of the processes that underlie the graphs and equations describing phenomena that dot the literature remain obscure. This is especially sad because neither the phenomena nor the functional relations between stimuli and phenomena are the essential answers to the great epistemological perplexity. Ultimately, the solution to this great problem must be one framed in terms of the processes that account for those relations.

I sincerely believe that the development of a satisfactory taxonomy will play an important antecedent role in the development of understanding about perceptual processing. But it must not be forgotten that a taxonomy is not a theory in the truest sense of the word. It is, at best, a prototheory that may provide some of the organization that is necessary before a truly analytic and reductionistic explanation can be constructed. If this book, at least, raises our awareness of the need for an acceptable taxonomy, it will have achieved whatever goals I had set for it at the outset.

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